IEA Bioenergy ExCo64, Liege, Belgium, 1/10/2009

Algae – The Future for Bioenergy?

Algae Biofuels: Challenges in Scale-up, Productivity and Harvesting (and Economics too!)

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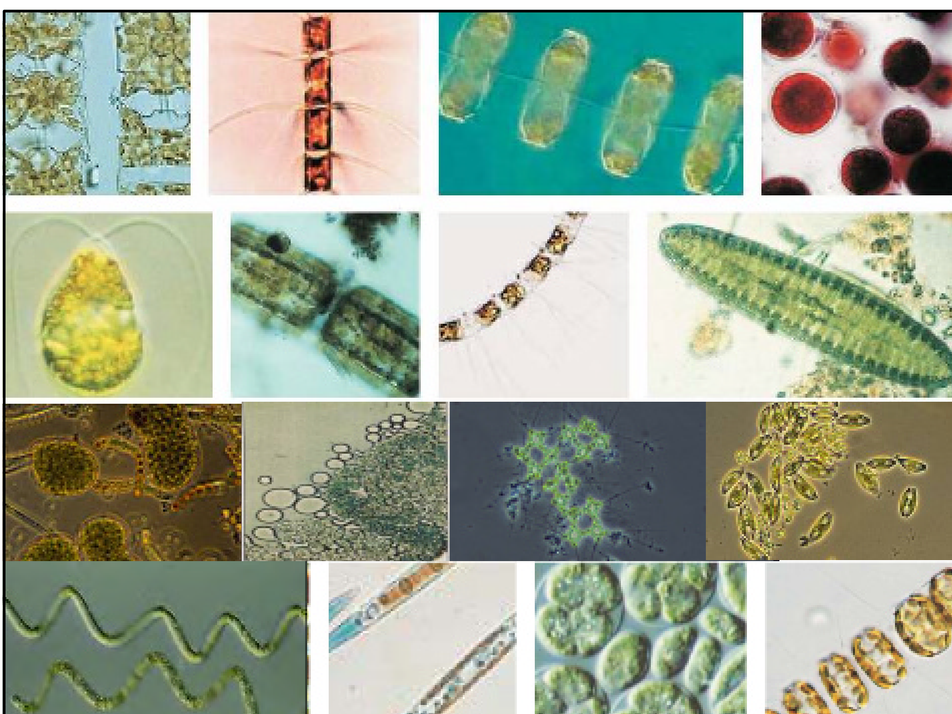

The Energy Journal, Vol. 1, No.1, 1980

Biomass Energy Economics

*John R. Benemann**

. . . an economy based only on solar energy would have to rely on the natural costless way of harnessing that energy, which means an intensive utilization of wood . . . and possibly, but at this moment, debatably, of algae.

N. Georgescu-Roegen, 1976

Challenges to Algae Biofuels Development

Microalgae are currently cultivated commercially (>100 mt/y) mainly in open shallow ponds, mostly in raceway-type, paddle wheel mixed ponds, for high value nutritional supplements, ~10,000 t/yr produced, with typical plant gate cost >$10,000/t.
The biofuels challenge: producing millions of tons at <$1,000/t

Microalgae are very small, grow as very dilute (<1 g/l) cultures in suspension, have very low standing biomass (<100 g/m2), require daily harvesting from large volumes of liquid, with the harvested biomass at <10% solids, must immediately process.

Microalgae cultures requires a source of CO2, either purchased or "free" (power plant flue gases, biogas or ethanol plants, etc.) Not often there were we want. CO2 use is a need not a virtue!

Microalgae require good climate – for a long cultivation season. For biofuels these must be produced at very high productivity And expand the number of species cultivated from four to more.

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1. Historical development of microalgae technology
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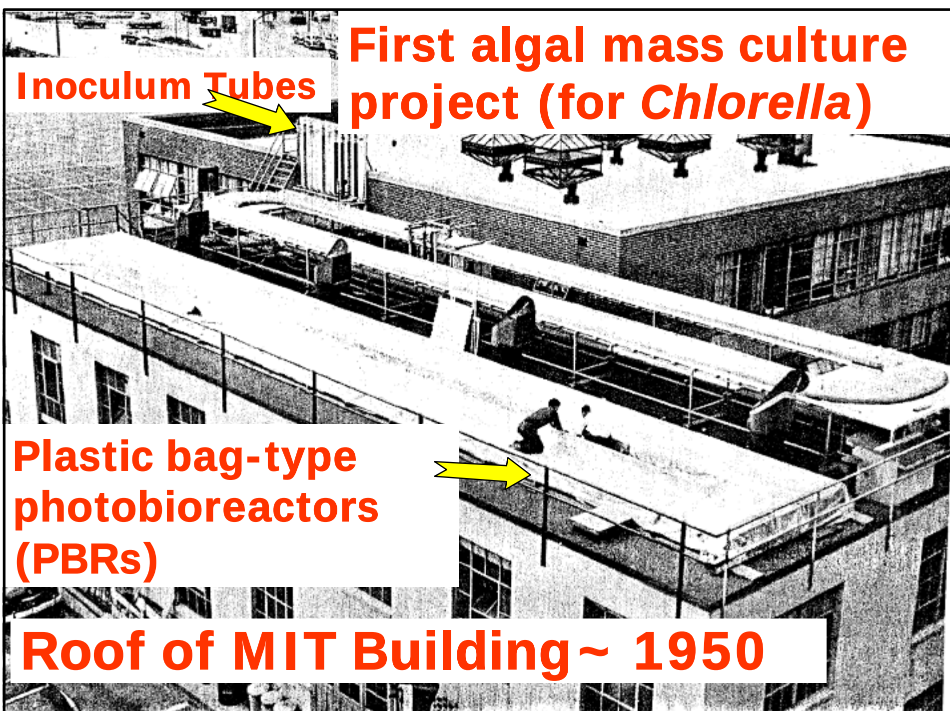
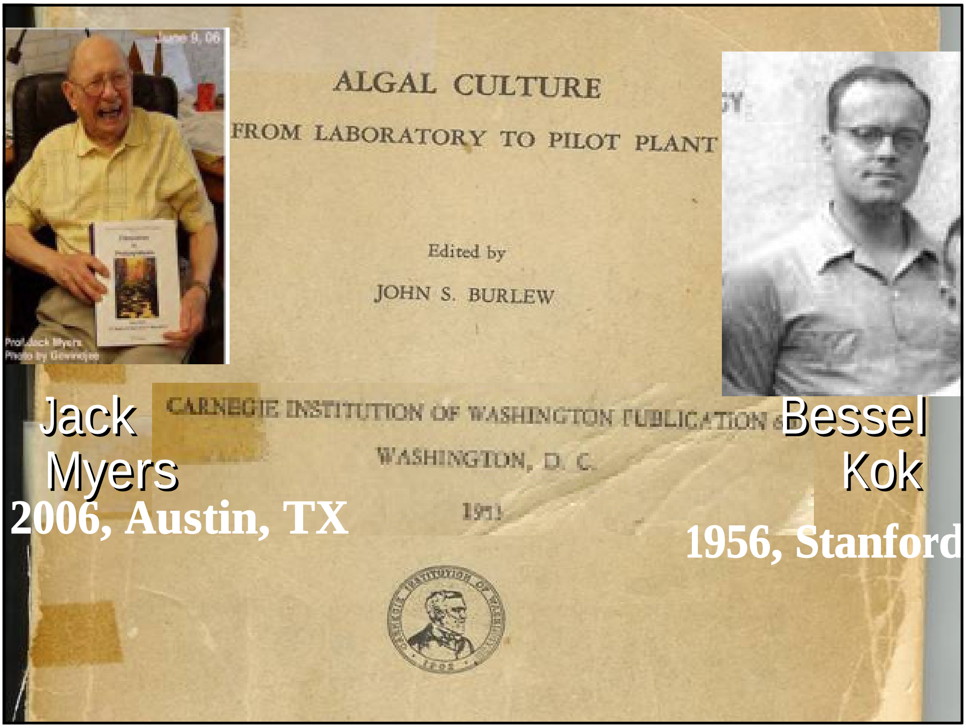
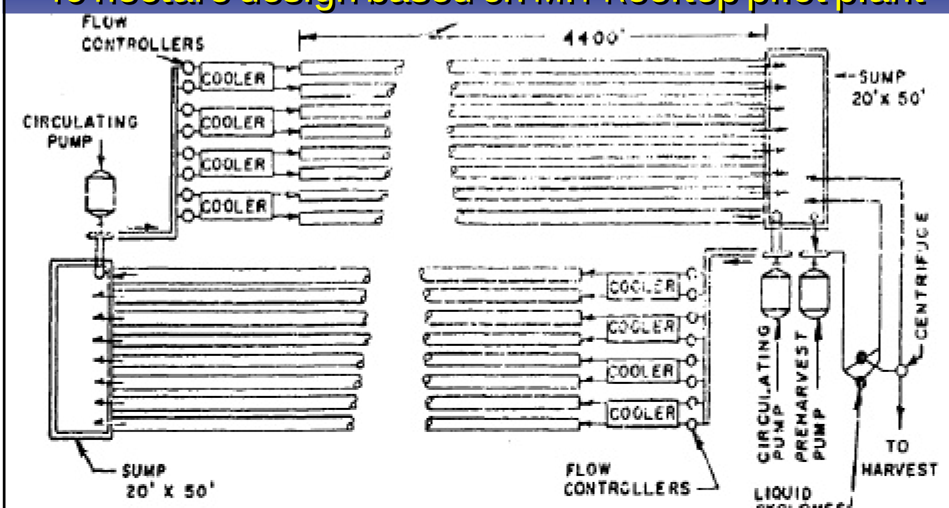




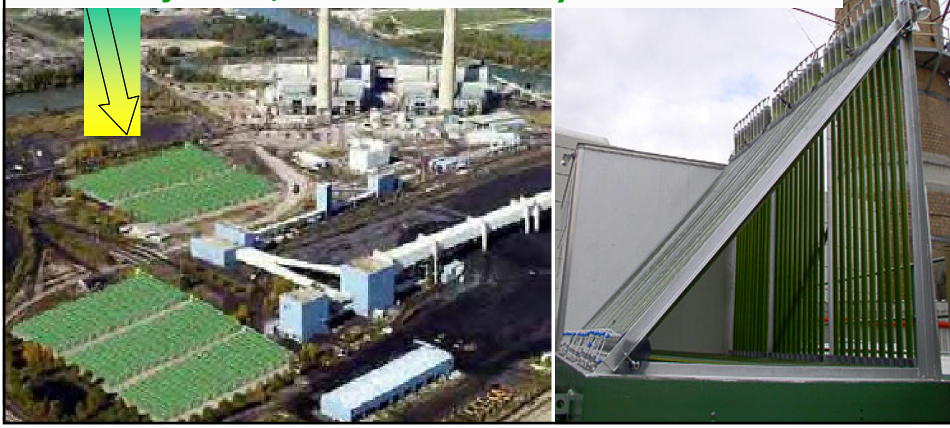
40 hectare design based on MIT Rooftop pilot plant

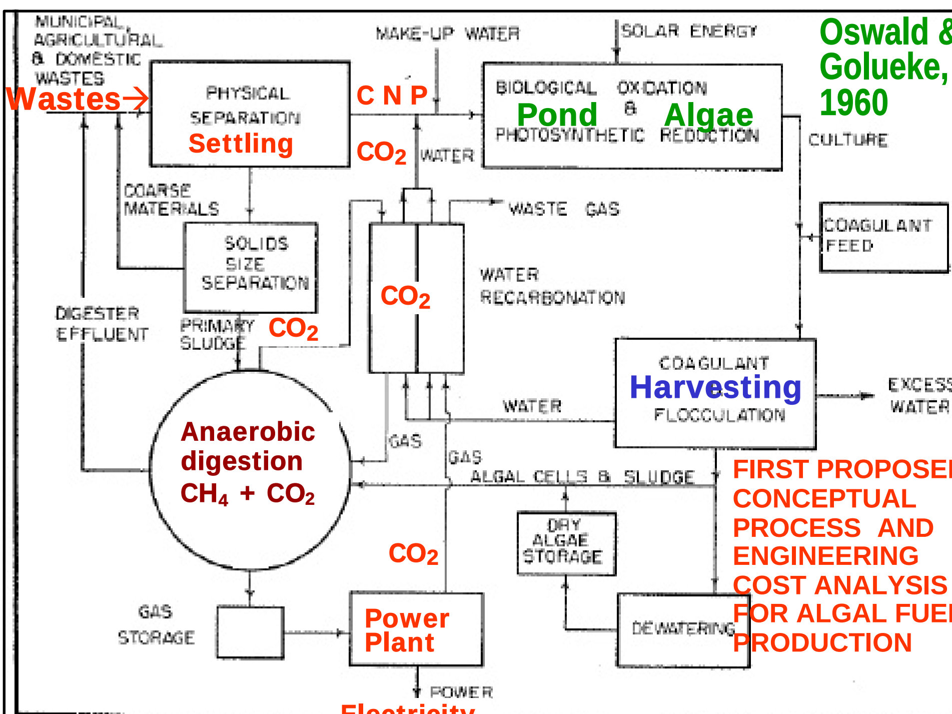


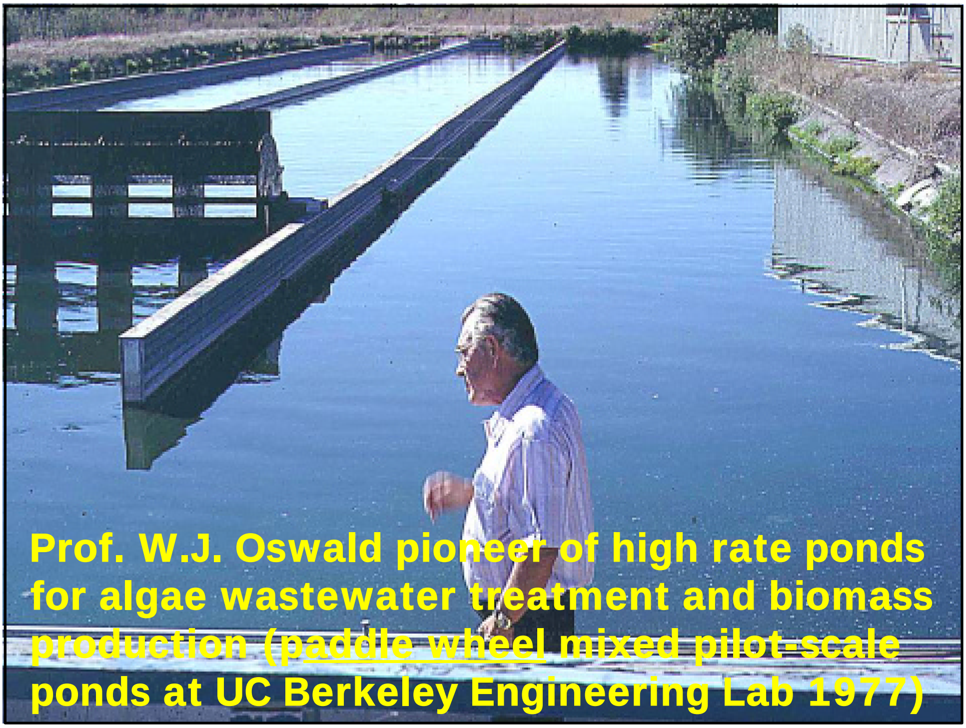
Fisher (1956), A.D. Little Co.: engineering design-cost estimate for 40 ha PBR system: 2009**$>2,000,000/ha** (plastic tubes ~5% of total) A rather detailed study!

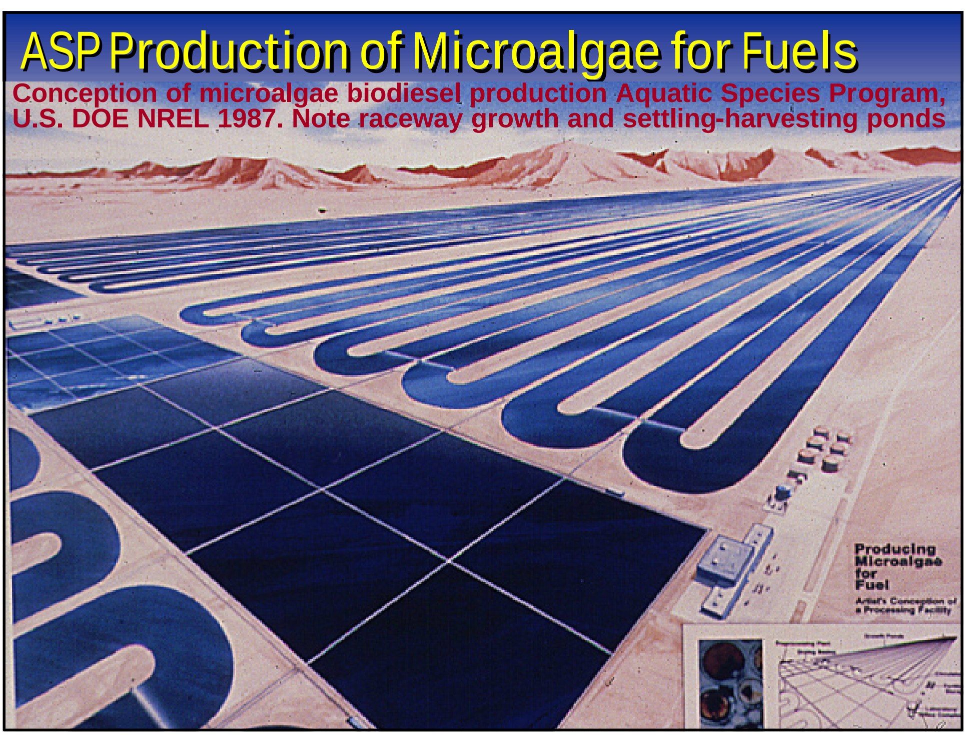
History repeating itself: GreenFuel Technologies

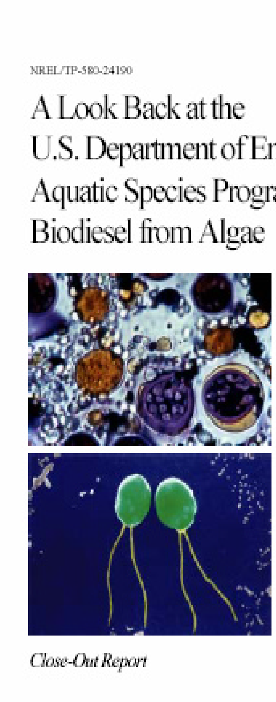
Roof of MIT at Campus power plant. Claimed that their PBRs captured 85% NOx & 50% CO2, and produced biodiesel at >250,000 l/ha-yr (!!!). The tested at Arizona Public Services power plant (photoshop!), tests failed…. Now are history (went broke May 2009, after $70 million).






Prof. W.J. Oswald pioneer of high rate ponds for algae wastewater treatment and biomass production (paddle wheel mixed pilot-scale ponds at UC Berkeley Engineering Lab 1977)


ASP Production of Microalgae for Fuels
Conception of microalgae biodiesel production Aquatic Species Program, U.S. DOE NREL 1987. Note raceway growth and settling-harvesting ponds
Producing Microalgae for Fuel
Artist's Conception of a Processing Facility



Paul Roessler (now at Synthetic Genomics)

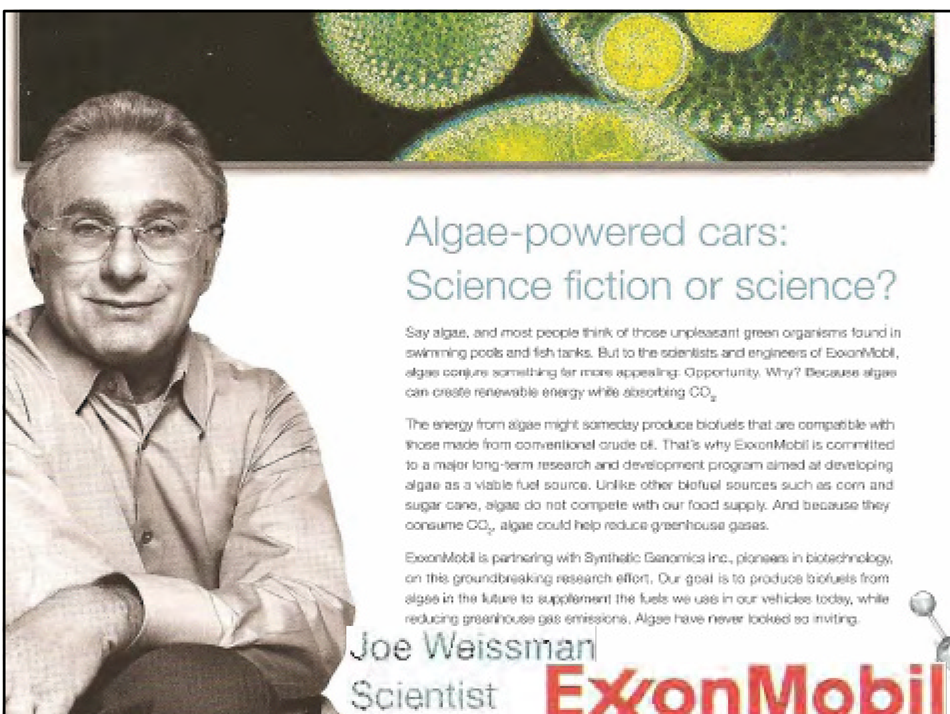
Aquatic Species Program Report 1998 .

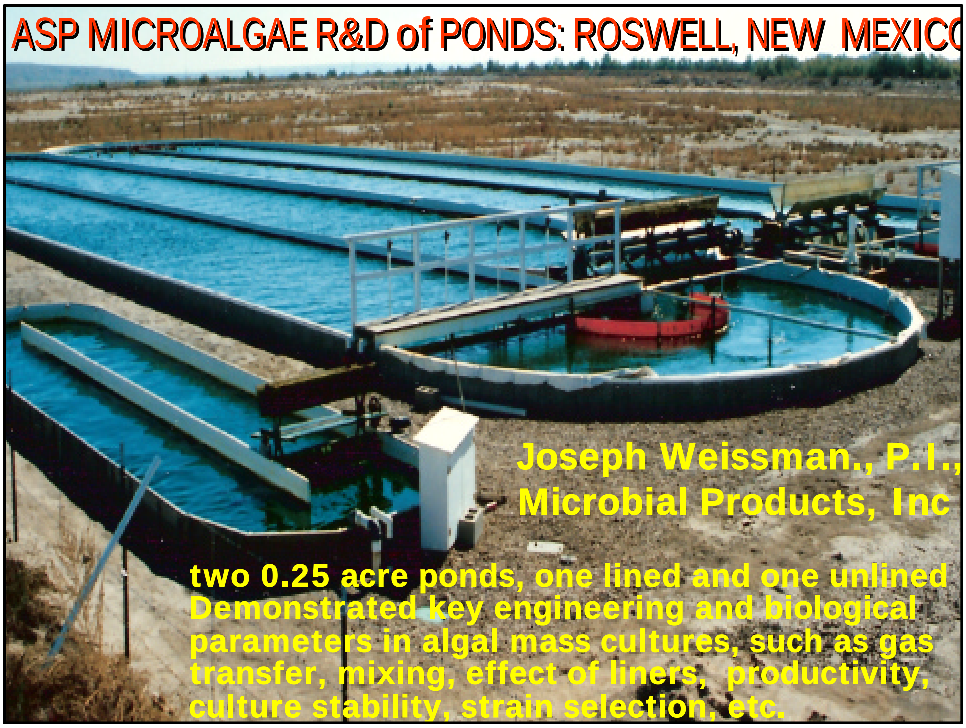
Executive Summary
J. Sheehan (NREL) et al.

Part 1. Algal Cultures and Genetics (P. Roessler and T. Dunahay, consultants)

Part 2. Algal Mass Cultures and Production Technology (J. Benemann, Principal Investigator, and J. Weissman, consultant).

<u>Report only summarizes extensive work by the ASP</u>





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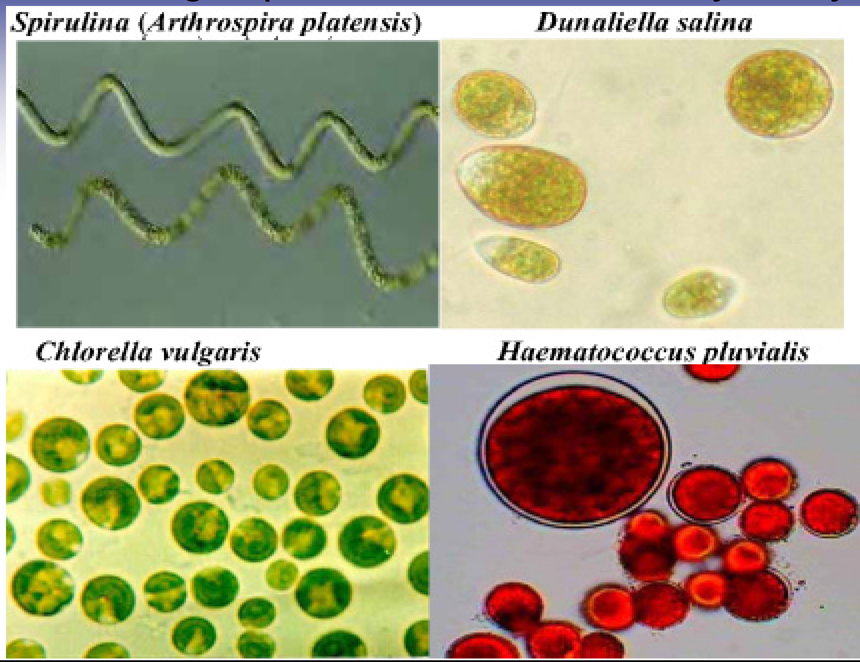
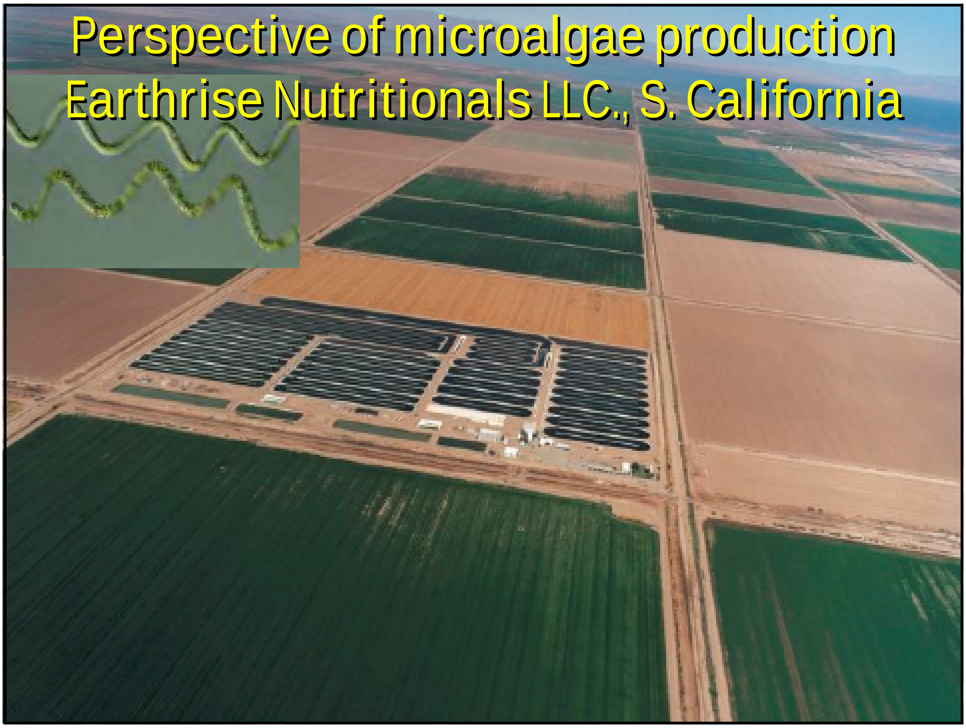
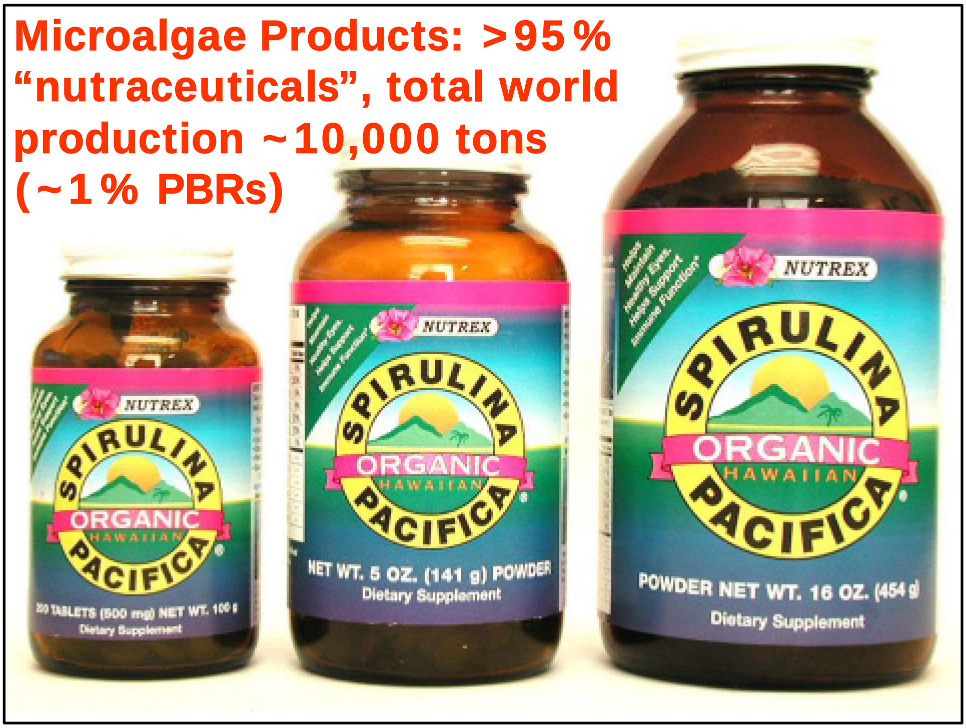
Microalgae produced commercially today



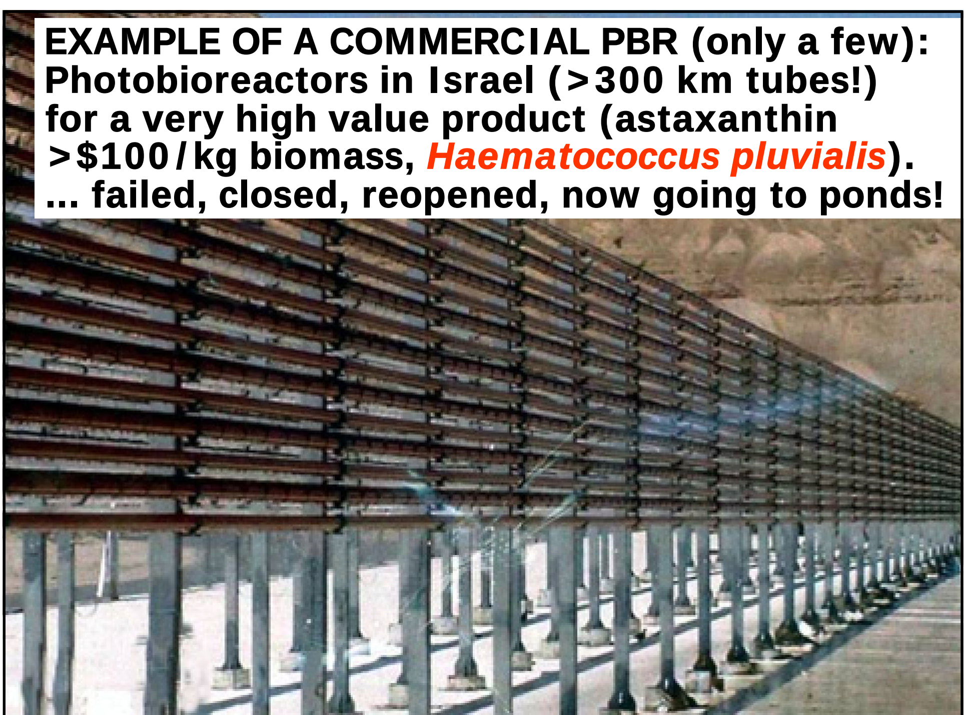
1st Commercial Algae Production 1960s: Chlorella In Japan, using circular ponds (these do not scale)


Perspective of microalgae production
Earthrise Nutritionals LLC., S. California


Dunaliella salina , NBT Israel (Ami BenAmotz]
CO2 →


Microalgae Products: >95% "nutraceuticals", total world production ~10,000 tons (~1% PBRs)
NUTREX
SPIRULINA
ORGANIC
HAWAIIAN
PACIFICA
NET WT. 5 OZ. (141 g) POWDER
Dietary Supplement
POWDER NET WT. 16 OZ. (454 g)
Dietary Supplement


2 MW(e) Power Plant and CO2 Capture
Tower at Cyanotech Corp., Hawaii


EXAMPLE OF A COMMERCIAL PBR (only a few):
Photobioreactors in Israel (>300 km tubes!)
for a very high value product (astaxanthin
>$100/kg biomass, *Haematococcus pluvialis*).
... failed, closed, reopened, now going to ponds!

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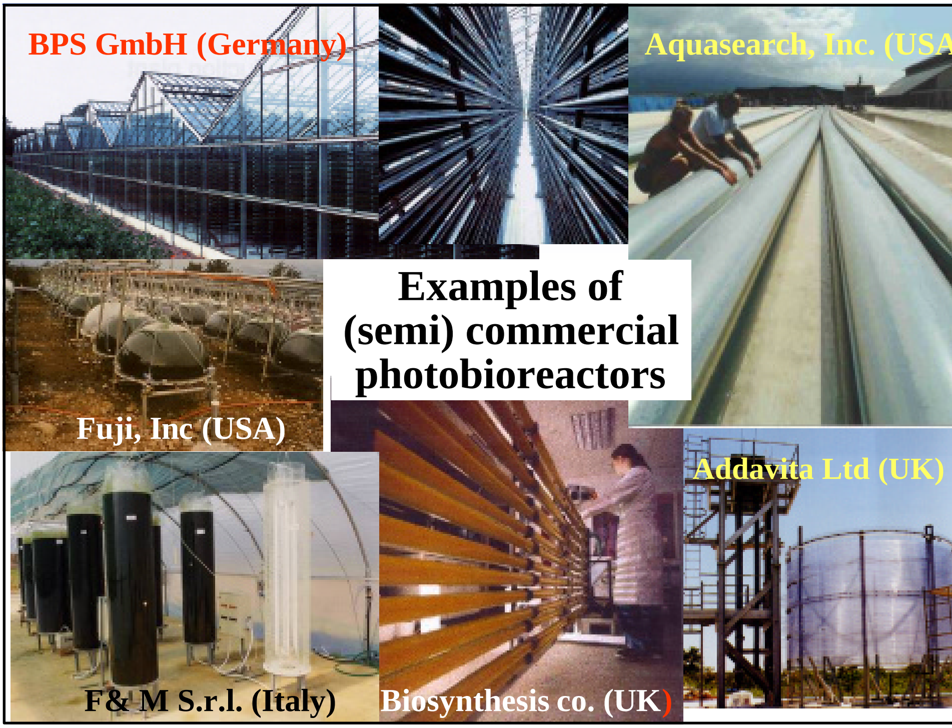


Biotechnology and Bioengineering, Vol. 31, Pp. 336–344 (1988)

Photobioreactor Design: Mixing, Carbon Utilization, and Oxygen Accumulation

Joseph C. Weissman* and Raymond P. Goebel
Microbial Products, Inc. 408A Union Ave., Fairfield, California 94533

John R. Benemann
Department of Applied Biology, Georgia Institute of Technology, Atlanta,

Photobioreactor design and operation are discussed in terms of mixing, carbon utilization, and the accumulation of photosynthetically produced oxygen. The open raceway pond is the primary type of reactor considered; however small diameter (1–5 cm) horizontal glass tubular reactors are compared to ponds in several respects.

Paper in response to many claims that PBRs superior to open ponds. Points out problems of both open ponds and closed PBRs. Main issue for PBRs scalability: unit size <1000 m^2. Also PBRs are <u>too expensive for biofuels</u> but good for inoculum (~1% of biomass) production.

Open Ponds vs. Closed Photobioreactors

Parameter	Relative Impact	Note
Contamination risk	Ponds > PBRs	Just a matter of time for either
Productivity	Ponds ~ PBRs	NO substantial difference*
Space required	Ponds ~ PBRs	A matter of productivity
Water losses	Ponds ~ PBRs	Evaporative cooling needed
CO2 losses	Ponds ~ PBRs	Depends on pH, alkalinity, etc.
O2 Inhibition	Ponds < PBRs	O2 major problem in PBRs
Process Control	Ponds ~ PBRs	no major differences (weather)
Biomass Concentration	Ponds < PBRs	function of depth, 2 -10 fold
Capital/Operating Costs	Ponds << PBRs	Ponds >>10 x lower cost!

*Productivity can be higher if PBRs are in vertical orientation or in cold conditions where the heat retained allows faster growth of the algae.

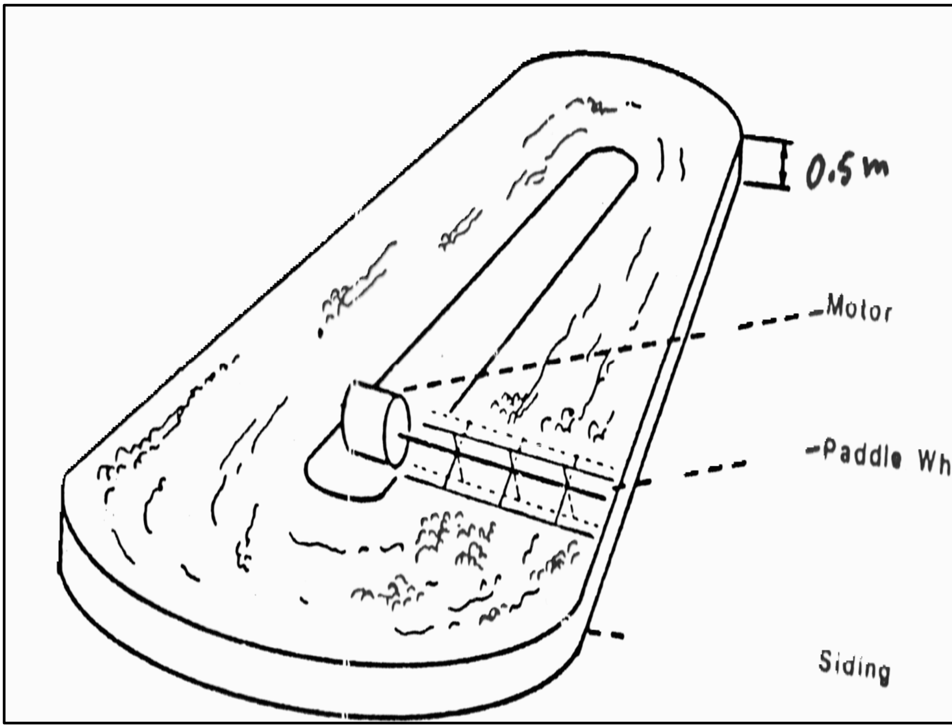
CONCLUSION: Are PBRs better than ponds? Sometimes: in cold climate, not in hot. Advantages overstated. Key issue is COST

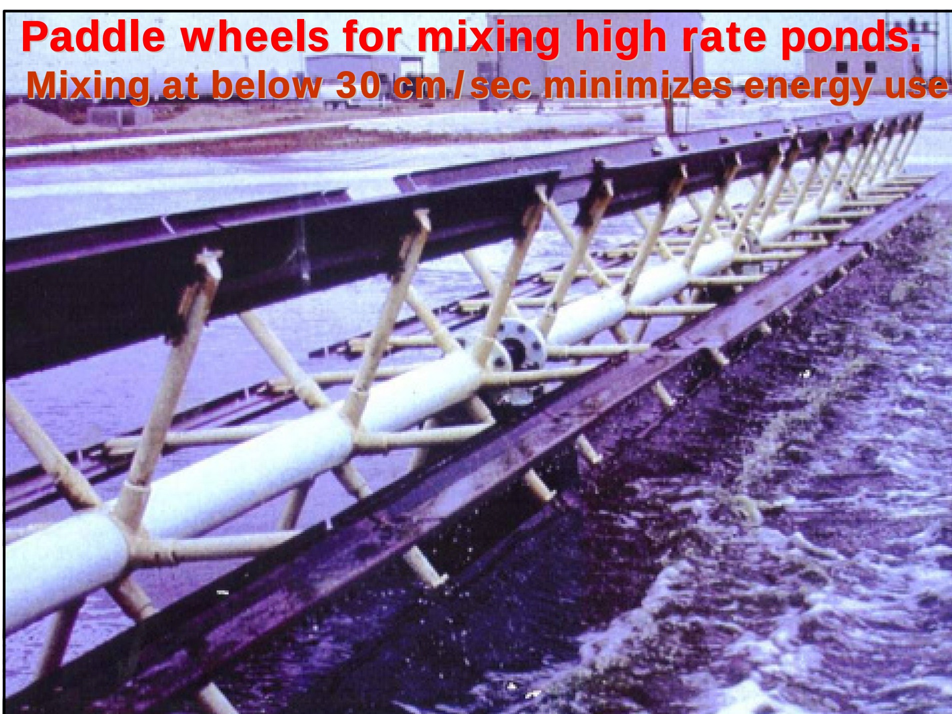
Algae biofuels proposed for Boston high-rise

Futuristic design concept offers ultimate in on-site fuel generation

Sept. 29, 2009 Biofuel Digest

Solix Pilot Plant, Colorado (Summer 2009)


0.5 m
Motor
Paddle Whe
Siding


Paddle wheels for mixing high rate ponds.
Mixing at below 30 cm / sec minimizes energy use

CO_2 Mass Transfer Coefficients in Ponds

Depth cm	Velocity cm/sec	k_L cm/sec	Surface Renewal, sec
10	10	3.9×10^{-4}	150
10	30	1.4×10^{-3}	12
30	10	2.2×10^{-4}	480
30	30	0.8×10^{-3}	37

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   INTERMISSION: CO2 sources /issues for algae biofuels

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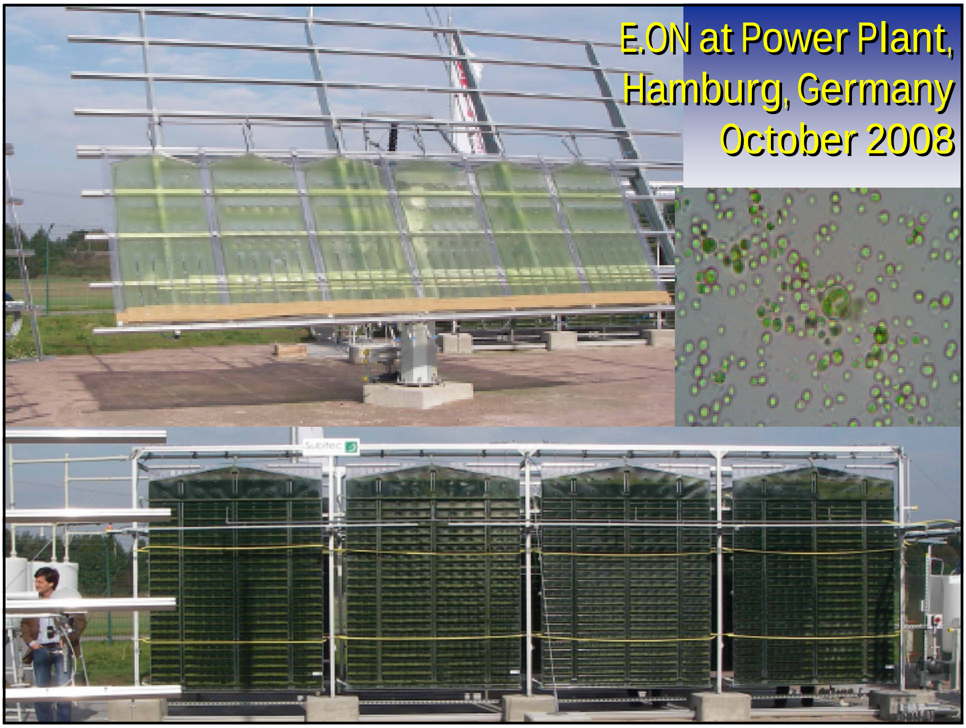
7. Conclusions: A few more barriers to algae biofuels



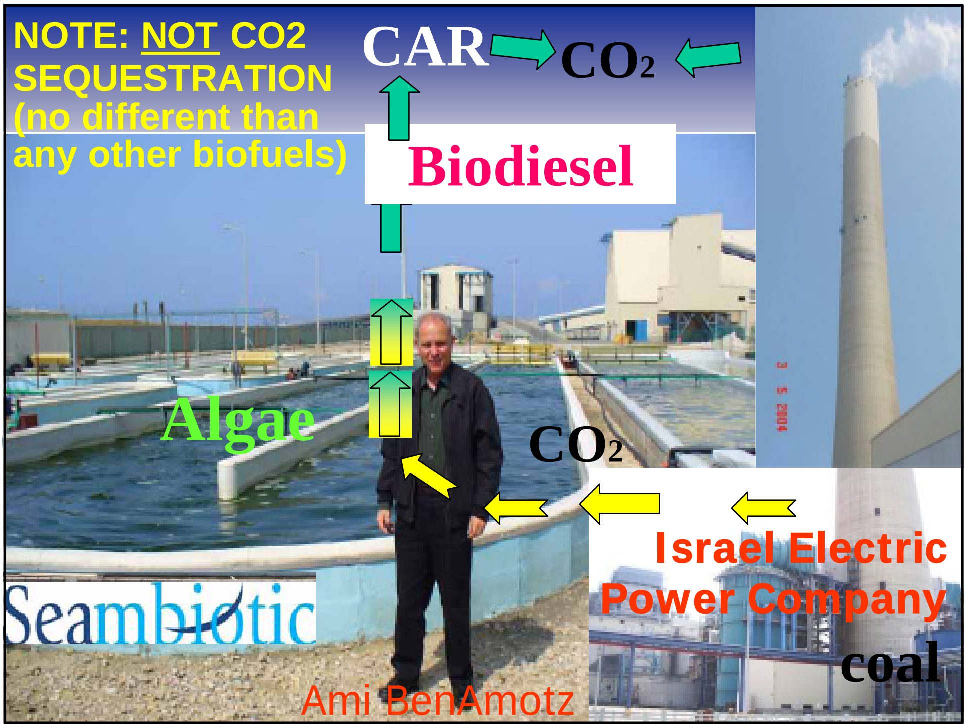
Algae use of large coal-fired power plant (CPP) CO_2

1. **Even a small CPP needs thousands of hectares of algae ponds**
2. **Transport of flue gas to the algae ponds is a major cost problem**
3. **Transfer of flue gas CO_2 into the ponds is another cost problem**
4. **Loss of CO_2 during transfer of flue gas into algae pond culture**
5. **Loss of CO_2 from the ponds by outgasing, before the algae grow**
6. **Must design CO_2 supply for highest summer hourly productivity**
7. **Day-night & winter-summer disparities reduce CO_2 use by ~75%**
8. **Only ~40-60% of CO_2 actually fixed by algae ends up in oil / fuel**
9. **With losses, <u>maximum</u> <u>plausible</u> net capture of CPPs CO_2 ~10%**
10. **Capture of CO_2 from CPPs is <u>NOT</u> greenhouse gas abatement**
11. **Biofuels grown on CPPs are NOT sustainable (by definition)**
12. **<u>CPPs MUST reduce CO_2 emissions by 90%, not just by ~10%</u>**
13. **Global potential for algae CO_2 capture from CPPs is <<1%**

ALGAE USE OF COAL-FIRED POWER PLANT FLUE GAS CO2 FOR GREENHOUSE GAS ABATEMENT CONCLUSION:

ABANDON ALL HOPE

Das RWE-Algen Projekt



Alternative Sources of CO2 for Algae Production

1. Gas/Oil fired cement or ammonia plants, refineries, etc.? Better
2. Small distributed fossil power plants? Better still, need more
3. Capture of CO_2 from air to supply the algae ponds? Not likely?
4. Seawater as a source of CO_2? OK, but only supplemental
5. Biomass power plants, pulp paper mills? Yes, need right place
6. Ethanol and other agricultural processing plants? More like it.
7. Municipal solid wastes processes (landfills)? Looking better !
8. Animal & other agricultural wastes? Looking better all the time!
9. Municipal wastewaters (sewage)? BINGO! We have a winner !!!

WHY?: Because municipal wastewater treatment pays, enough;
Because sewage has the right C, N, P nutrient concentrations;
Because it is a reliable supply, and algae treatment would save more greenhouse gases by producing not using energy;
Because algae recover nutrients better than other technologies
Because use existing technology, need only modest advances

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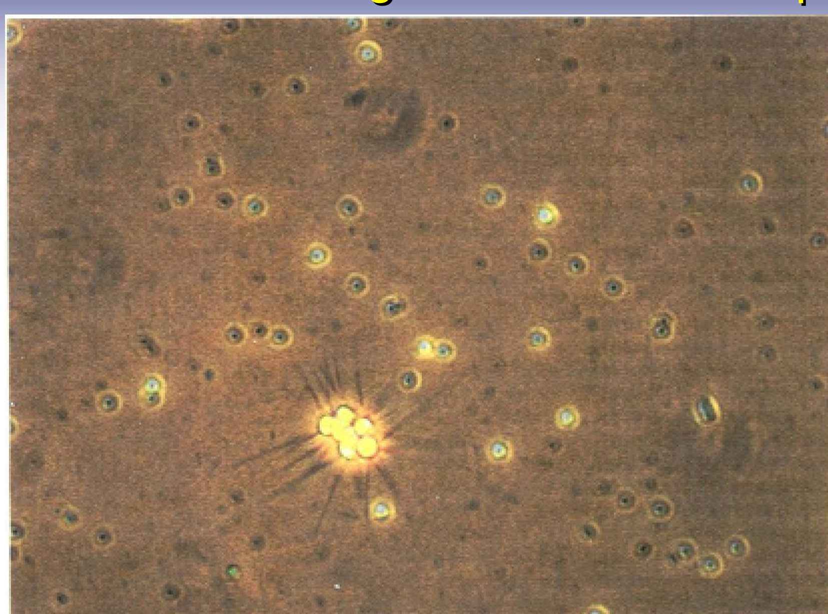
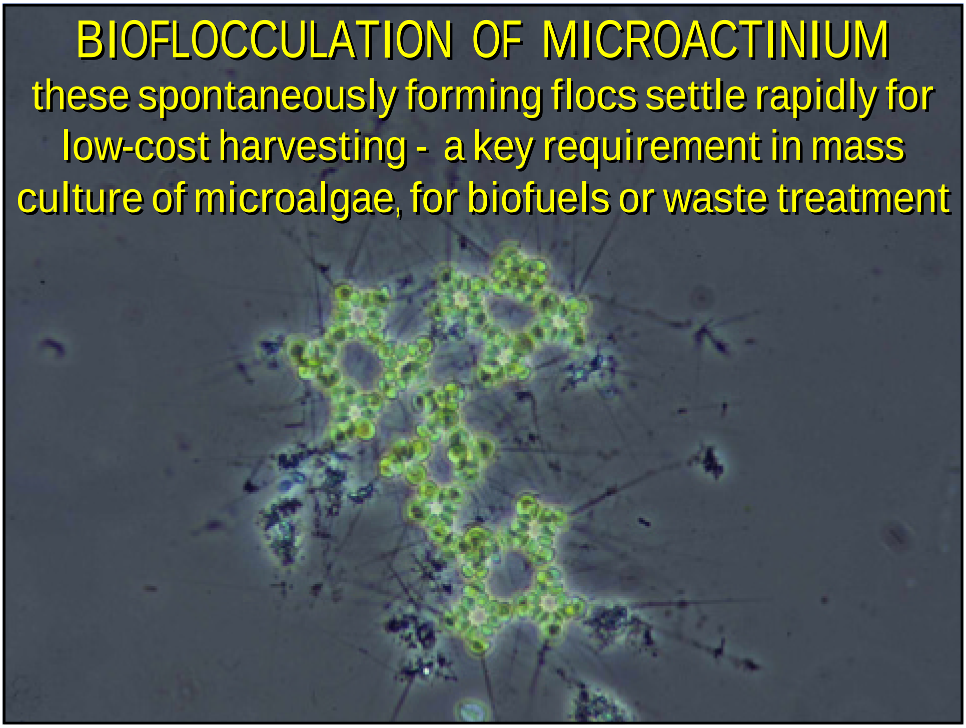
MICROALGAE FOR WASTEWATER TREATEMENT

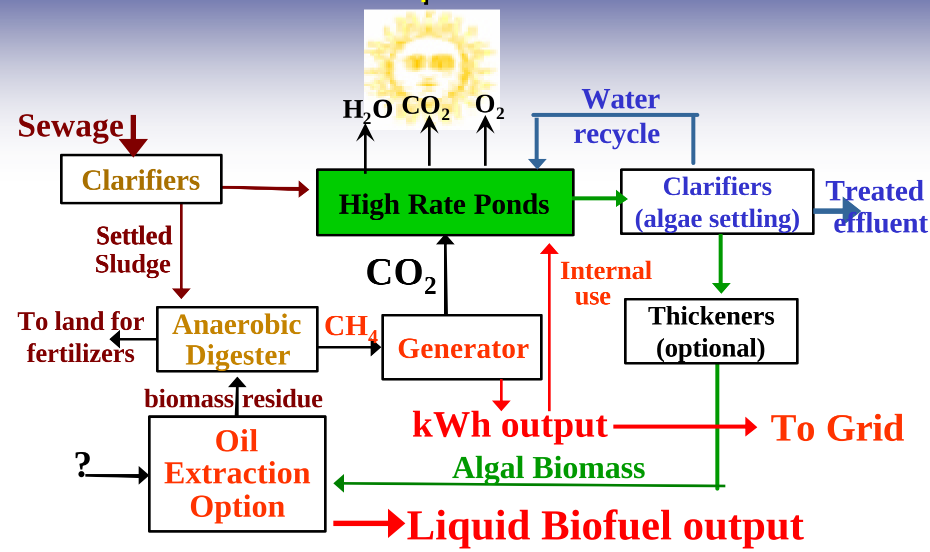
Napa, CA, Wastewater Treatment Ponds ~ 100 hectare

Micractinium in high rate wastewater pond




BIOFLOCCULATION OF MICROACTINIUM
these spontaneously forming flocs settle rapidly for
low-cost harvesting - a key requirement in mass
culture of microalgae, for biofuels or waste treatment

Schematic for Municipal Wastewater Treatment



with nutrient capture, oil and biogas co-products

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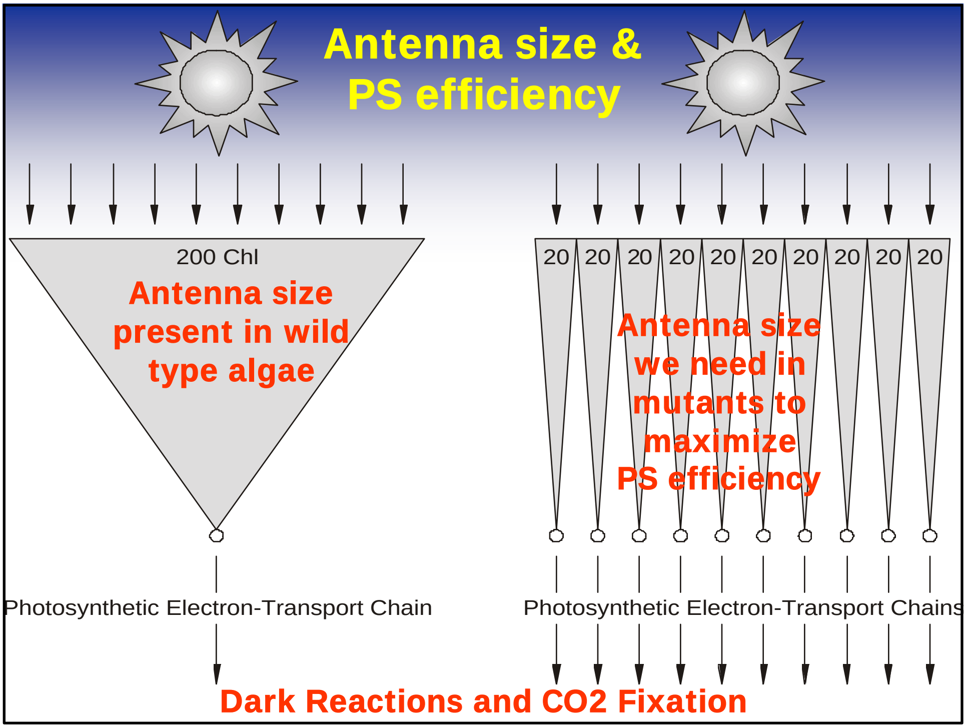
THE ALLURE OF MICROALGAE OIL PRODUCTION

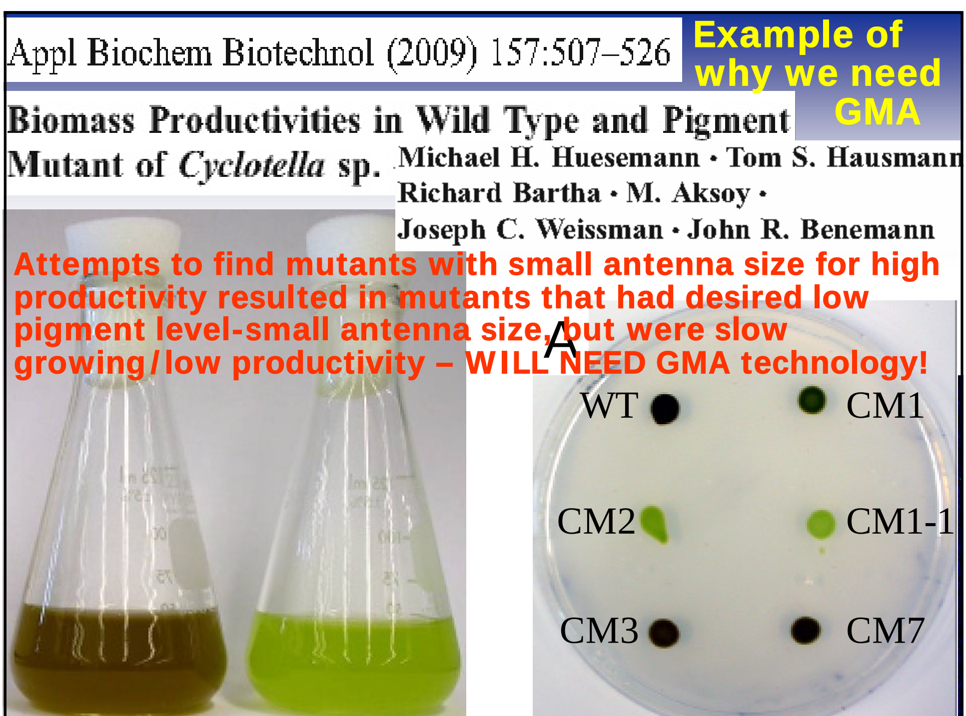
Oil yields	liters/ha-yr	barrels/ha-yr
Soybeans	400	2.5
Sunflower	800	5
Canola	1,600	10
Jathropha	2,000	12
Palm Oil	6,000	36
Microalgae	60,000-240,000*	365 -1500*

*Projected high yield (by GreenFuel Technologies) is ~2 x theoretical efficiency (with no biomass!)
Low is maximum possible yield for long-term R&D

SOLAR ENERGY CONVERSION WITH PHOTOSYNTHESIS

US Southwest solar energy=2 MWhr (7.2 GJ)/m^2-yr
~assume 90% reaches the crop/or algae in pond
~45% is PAR (photosynthetic active radiation)
~ 90% photons are absorbed by PS pigments
22% max PS efficiency (photons→biomass energy)
~75% loss to light saturation and photoinhibition
~15% loss to respiration (growth, maintenance)
Calculation (current best, year-round algae culture):
7.2 GJ x0.9 x0.45 x0.9 x0.22 x0.25 x0.85 = 0.12 GJ
~1.7% solar efficiency. For @25% oil in biomass
~23GJ/mt and productivity is ~52 m=13 mt oil/ha-y
Maximum oil ~15,000 liters/ha-yr (1,600 gal/ac-yr)
near-term technology, 2-3X with long-term R&D on PS efficiency (“antenna size”), oil biosynthesis, etc


Antenna size &
PS efficiency
200 Chl
Antenna size present in wild type algae
20 20 20 20 20 20 20 20 20 20
Antenna size we need in mutants to maximize PS efficiency
Photosynthetic Electron-Transport Chain
Photosynthetic Electron-Transport Chains
Dark Reactions and CO2 Fixation


Appl Biochem Biotechnol (2009) 157:507–526
Example of why we need GMA
Biomass Productivities in Wild Type and Pigment Mutant of *Cyclotella* sp.
Michael H. Huesemann · Tom S. Hausmann
Richard Bartha · M. Aksoy ·
Joseph C. Weissman · John R. Benemann
Attempts to find mutants with small antenna size for high productivity resulted in mutants that had desired low pigment level-small antenna size, but were slow growing/low productivity – WILL NEED GMA technology!
A
WT
CM1
CM2
CM1-1
CM3
CM7

For biofuels we will not only need ponds but also Genetically Modified Algae (GMA)

1. For high productivity/oil content we most liekely will need GMA
2. These genetic modifications are of a regulatory nature, do not involve introduction of foreign genes or novel pathways.
3. There is little /no difference between genetic modifications using molecular tools and natural selection or mutagenesis. However: the latter not as powerful, specific or fast.
4. GMAs) pose no risk to the environment, will not spread.
5. HOWEVER, many, both lay and scientists, view use of GMA, and their unavoidable dispersal with concern, even alarm.
6. We need a committee of phytoplankton ecologists and other independent experts who can advise regulators, government officials and the public about these issues and safety of GMA.
7. I called for a moratorium on GMA releases (but not R&D) until this process is completed. Anyway, no rush, we are not ready.

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Prior techno-economic analyses for open pond microalgae biofuel production (most now available at http://www.osti.gov/bridge/)

Benemann, J.R. P. Pursoff, & W.J. Oswald, **1978. Engineering Design and Cost Analysis of a Large-Scale Microalgae Biomass System**, Final Report US DOE. NTIS #H CP/T1605-01 UC-61.

Benemann, J.R., R.P. Goebel, J.C. Weissman, & D.C. Augenstein **1982. Microalgae as a source of liquid fuels**. Final Report U.S.DOE BER

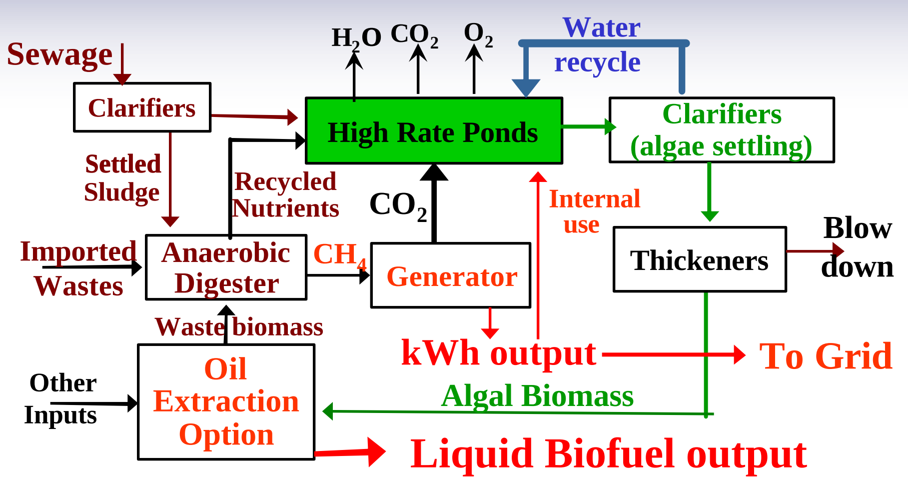
Weissman, J.C., & R.P. Goebel, **1987**. **Design and analysis of microalgal open pond systems for the purpose of producing fuels** Report to US DOE- SERI (for the Aquatic Species Program)

Benemann, J.R. & W.J., Oswald **1996**, **Systems and economic analysis of microalgae ponds for conversion of CO2 to biomass.** Report to US DOE-NETL (National Technology Energy Laboratory)

Caution: These reports lack in design and cost details – and made many very favorable assumptions about process.

Conclusion: it may not be impossible to produce algae biofuels

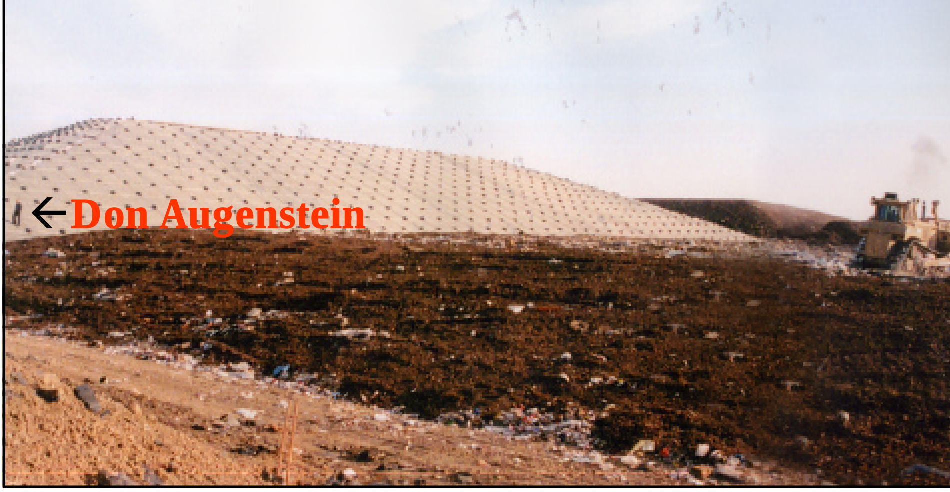
Updated Engineering Design Cost Analysis Project 2009 (Energy Biosciences Institute, UC Berkeley/LBL) Lundquist (Cal Poly), Woertz (MicroBio Engineering, Inc.) et al.



Oil + Biogas production, water +nutrients recycled

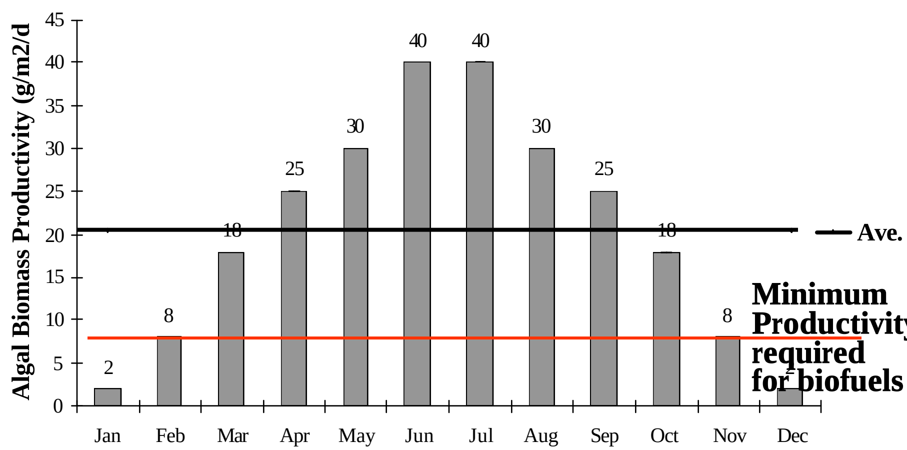
Controlled Bioreactor Landfill Project, Davis CA

1989 – present Don Augenstein and John Benemann Institute for Environmental Management, Inc. and Ramin Yazdani, Dept. Public Works, Yolo County, CA

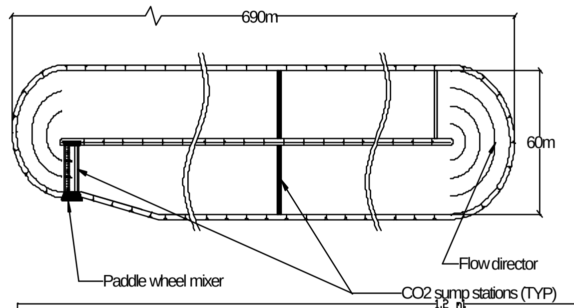


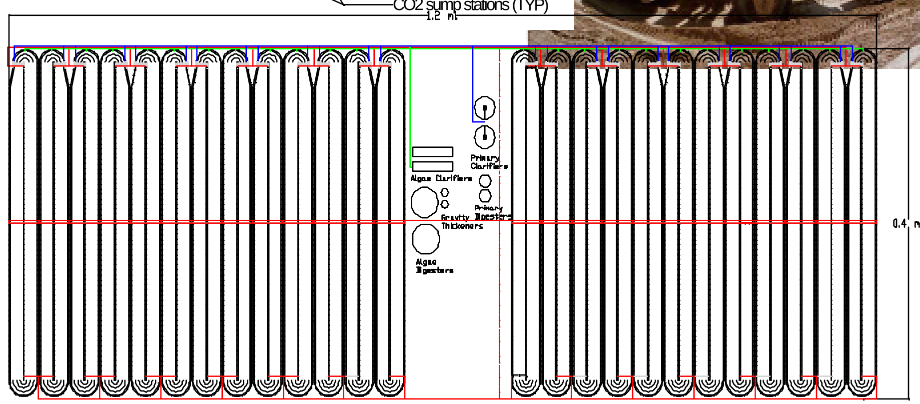
Southern California climate and optimistic productivities assumed

- Annual daily average projected at = 20 g/m2/d
- Max = 4 g/m2/hr for designs of ducts, pipes, pumps, etc.



Pond Design Layout and Construction (Ag. engineering!)





	A B C D E F	G	H	I	J	K	L	M	N	O	P	Q	R
1	**Recycle wastewater case**												
2	Set Price for Land (50% increase for >100ha)		15,000	$/ha									
3	Set Price for Barrel of Oil		180	$/barrel	Soy bean oil cost as of 2007								
4	Set Price for Carbon Credit		1.85	$/mt	As of 10-08-08								
5	Gas Turbine Cost ($/kW)	$	475	/kW	REF Boyce 2002								
6	Additional area req. `based on drawing		39%										
7													
8													
9													
10													
11													
12	**Operation**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
13	Average algae productivity (g/m2/d)	2	8	18	25	30	40	40	30	25	18	8	2
14	Evaporation of total flow (%)	2.5%	3.4%	5.5%	7.3%	9.2%	9.6%	9.7%	9.1%	7.4%	5.5%	3.3%	2.4%
15	Volatilazation N (%)	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
16	Blow down (%)	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
17	Anaerobic digestion loss (%)							10%					
18													
19	**Operation Results**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
20	Influent (m3/d)	311,400	311,400	311,400	311,400	311,400	311,400	311,400	311,400	311,400	311,400	311,400	311,400
21	Total Flow Q (m3/d)	80,607	81,353	82,626	83,541	84,207	85,569	85,569	84,207	83,541	82,626	81,353	80,607
22	Total area req. (ha)	100	101	103	104	105	107	107	105	104	103	101	100
23	# of Ponds	25	25	26	26	26	27	27	26	26	26	25	25
24	Evaporation (m3/d)	2,018	2,773	4,555	6,030	7,713	8,179	8,253	7,649	6,129	4,475	2,642	1,887
25	Blow down Q (m3/d)	77,718	76,610	74,226	72,318	70,319	69,205	69,132	70,383	72,219	74,306	76,742	77,849
26	Blow down N (mg/L)	28	24	19	15	12	5	5	12	15	19	24	26
27													
28	Total Biomass Available (kg/d)	1,620	6,539	14,942	20,983	25,380	34,388	34,388	25,380	20,983	14,942	6,539	1,620
29	Total Biomass per month (kg/month)	48591	196161	448272	629493	761410	1031645	1031645	761410	629493	448272	196161	48591
30													
31	**Labor Requirements**												
32	$/ha/yr	$ 3,349	$ 3,343	$ 3,333	$ 3,325	$ 3,320	$ 3,309	$ 3,309	$ 3,320	$ 3,325	$ 3,333	$ 3,343	$ 3,349
33	$/yr	$ 378,194	$ 380,243	$ 383,755	$ 386,290	$ 388,141	$ 391,946	$ 391,946	$ 388,141	$ 386,290	$ 383,755	$ 380,243	$ 378,194
34													
35													
36	**Carbon Dioxide**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
37	**Peak hourly**												
38	Peak Algae Productivity (g/m2/hr)	0.5	0.5	0.5	2	4	4	4	4	3	2	0.5	0.5
39	Max Biomass (kg/hr)	536	536	536	2143	4286	4286	4286	4286	3214	2143	536	536
40	C needed (kg/hr)	268	268	268	1,071	2,143	2,143	2,143	2,143	1,607	1,071	268	268
41	CO2 Required with uptake eff. (kg/hr)	1,323	1,323	1,323	5,291	10,582	10,582	10,582	10,582	7,936	5,291	1,323	1,323
42	CO2 Req. (m3/hr)	962	962	962	3,850	7,700	7,700	7,700	7,700	5,775	3,850	962	962
43	Flue Gas Req. (m3/hr)	9,625	9,625	9,625	38,498	76,997	76,997	76,997	76,997	57,747	38,498	9,625	9,625
44	Flue Gas Req. (ft3/min)	5,665	5,665	5,665	22,659	45,318	45,318	45,318	45,318	33,989	22,659	5,665	5,665
45													
46	**Daily**												
47	Biomass produced (kg/d)	2,000	8,072	18,447	25,905	31,334	42,455	42,455	31,334	25,905	18,447	8,072	2,000
48	C needed minus recycled C and WW C (kg/day)	0	417	4,925	8,133	10,469	15,307	15,246	10,379	8,063	4,829	343	0
49	CO2 Required with uptake eff. (kg/d)	0	2,060	24,321	40,163	51,698	75,589	75,291	51,254	39,820	23,847	1,692	0
50	CO2 Req. (m3/hr)	0	107	1,264	2,087	2,687	3,929	3,913	2,664	2,070	1,239	88	0
51	Flue Gas Req. (m3/hr)	0	1,071	12,641	20,875	26,870	39,287	39,132	26,639	20,696	12,394	879	0
52	Flue Gas Req. (ft3/min)	0	630	7,440	12,286	15,815	23,123	23,032	15,679	12,181	7,295	517	0
53													
54	**Parasitic Energy**												
55	Water pumping (filling HRP) (kWh/d)	1,560	1,574	1,599	1,617	1,630	1,656	1,656	1,630	1,617	1,599	1,574	1,560
56	HRP mixing (kWh/d)	10,196	10,196	10,196	10,196	10,196	10,196	10,196	10,196	10,196	10,196	10,196	10,196
57	Solvent Extraction (kWh/d)	1,065	1,300	1,703	1,992	2,202	2,634	2,634	2,202	1,992	1,703	1,300	1,065
58	Primary Sludge pumping (kWh/d)	984	984	984	984	984	984	984	984	984	984	984	984
59	Blowers for Flue gas (kWh/d)	0	138	1,629	2,690	3,462	5,062	5,042	3,432	2,667	1,597	113	0
60	Setted algae pumping (2 times) (kWh/d)	44	178	406	570	690	935	935	690	570	406	178	44
61	Total Energy Consumption (kWh/d)	13,849	14,371	16,517	18,049	19,164	21,466	21,446	19,134	18,026	16,485	14,346	13,849
62	Total Energy Consumption (kWh/month)	415,474	431,121	495,503	541,461	574,921	643,990	643,391	574,030	540,771	494,550	430,380	415,474
63	Value ($/day)	$ 1,385	$ 1,437	$ 1,652	$ 1,805	$ 1,916	$ 2,147	$ 2,145	$ 1,913	$ 1,803	$ 1,649	$ 1,435	$ 1,385
64	Value ($/month)	$ 41,547	$ 43,112	$ 49,550	$ 54,146	$ 57,492	$ 64,399	$ 64,339	$ 57,403	$ 54,077	$ 49,455	$ 43,038	$ 41,547
65													
66	**Total Energy Produced (kWh/month)**	509,697	707,811	1,046,269	1,289,558	1,466,658	1,829,447	1,829,447	1,466,658	1,289,558	1,046,269	707,811	509,697
67	**Value of Total Energy Produced ($/month)**	$ 50,970	$ 70,781	$ 104,627	$ 128,956	$ 146,666	$ 182,945	$ 182,945	$ 146,666	$ 128,956	$ 104,627	$ 70,781	$ 50,970
68	**Net Energy Produced (kWh/month)**	94,223	276,690	550,766	748,097	891,737	1,185,457	1,186,057	892,628	748,788	551,719	277,431	94,223

100 ha Oil+Biogas+ wastewater treatment preliminary cost estimate

Total capital cost = $23 Million

Financial summary	
Total revenue from electricity ($/yr)	$800,000
Total operating expenses ($/yr)	($2,100,000)
Bond repayment ($/yr)	($2,000,000)
Total cash outlay requirements ($/yr)	**($3,300,000)**
Total oil produced (bbl/yr)	10,100
Total cash outlay per barrel ($/bbl)	**($327)**

Not Included: income, property taxes, wastewater treatment revenues, depreciation, corporate overheads, license fees ...

LCA GREENHOUSE GAS EMISSIONS & COSTS OF ALGAE BIODIESEL

Diesel trucks: algae vs. canola biodiesel/fossil diesel
Summary LCA Study by Campbell et al., 2009 based on Benemann & Oswald,1996, "conservative" case: productivity of 55 mt/ha-yr, 40% oil, ~20,000 l/ha-yr

Emissions & Costs for moving 1 mt 1 km by diesel truck	Algae 100%CO2	Algae Flue Gas	Canola biodiesel	Diesel Fossil
GHG CO_2e emissions g/t-mi	-22.7	-15.2	95.3	108.8
Cost, feedstock or algae ops	0.015	0.013	0.035	0.026
Cost, conversion & dist	0.006	0.007	0.007	0.003
Cost, capital	0.014	0.019	0.001	0.000
TOTAL COST $/mt-km	0.044	0.039	0.042	0.038

CO_2e: total greenhouse gases, includes CH_4 and N_2O. Costs do not include taxes. (Costs are relative: not adjusted from AUS$, cost of oil, etc.). For 100% CO_2 case, purchased CO_2

OUTLINE OF TALK

1. **Historical development of microalgae technology**
2. **Current commercial reality of microalgae production**
3. **Scale-up: closed photobioreactors vs. open ponds**
4. **Harvesting: wastewater treatment by microalgae**
5. **Productivity: reality, fantasy and genetic engineering**
6. **Economics: projected for microalgae biofuels**
7. **Conclusions: just a few more R&D challenges: the algae, the grazers, the climate, the, oh yes the oil!**

ASP Isolated many algal strains, tested for mass cultures

Each species, even each strain has its own story

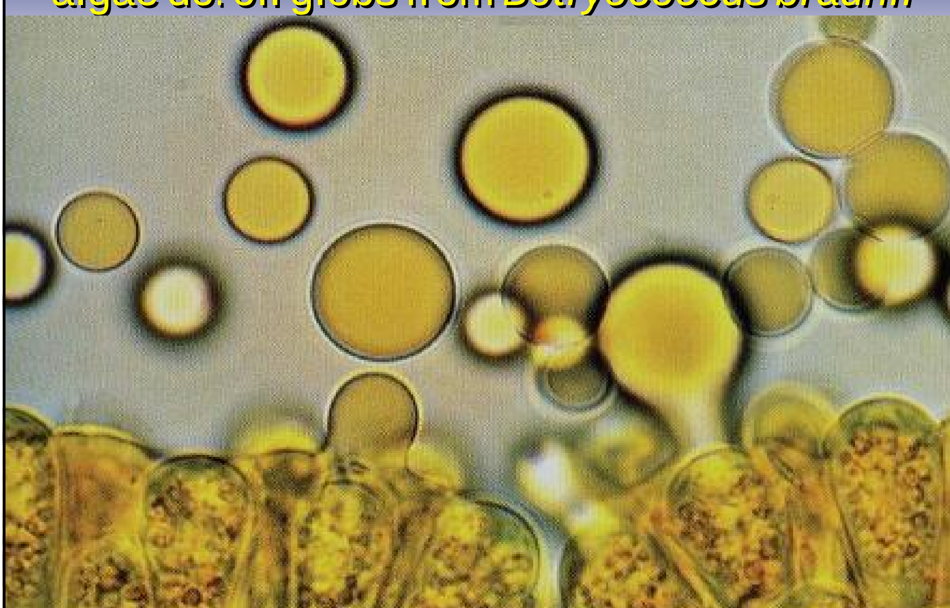
11 Division, 29 classes (vs. 2/12 vascular plants)

30 000 described species (< 10% of estimated)

ROTIFERS (JUST ONE TYPE OF ALGAE GRAZER]

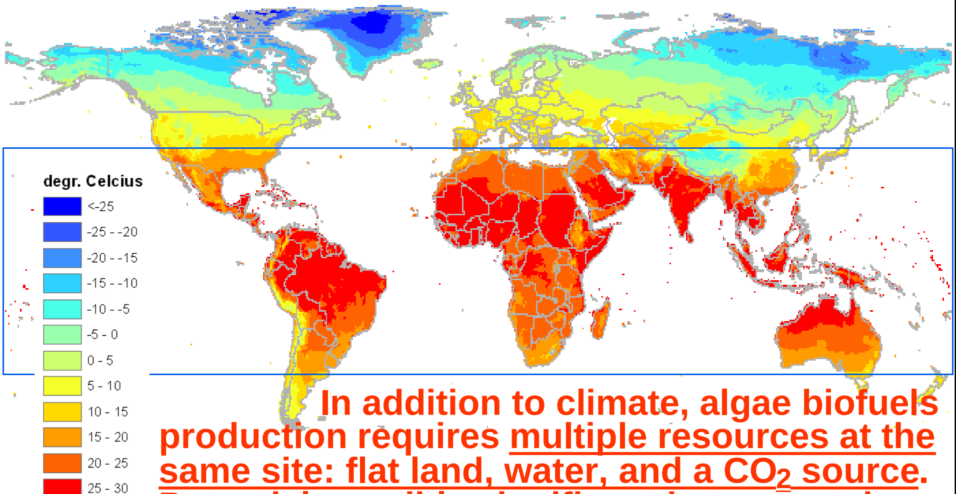
Must manage ponds for algal species & culture stability

Nature already provides what some want to make algae do: oil globs from *Botryococcus braunii*



A major issue: what is potential resource ?

Suitable climatic regions for microalgae : annual average temperatures of > 15 °C



In addition to climate, algae biofuels production requires <u>multiple resources at the same site: flat land, water, and a CO_2 source</u>. Potential possibly significant but uncertain

The Energy Journal, Vol. 1, No.1, 1980

Biomass Energy Economics

*John R. Benemann**

. . . an economy based only on solar energy would have to rely on the natural costless way of harnessing that energy, which means an intensive utilization of wood . . . and possibly, but at this moment, debatably, of algae.

N. Georgescu-Roegen, 1976

SO, WHY BOTHER WITH ALGAE BIOFUELS?

Algae R&D faster. Why? One week is like a crop year.

Algae R&D cheaper. Why? Smaller scales, fewer variables

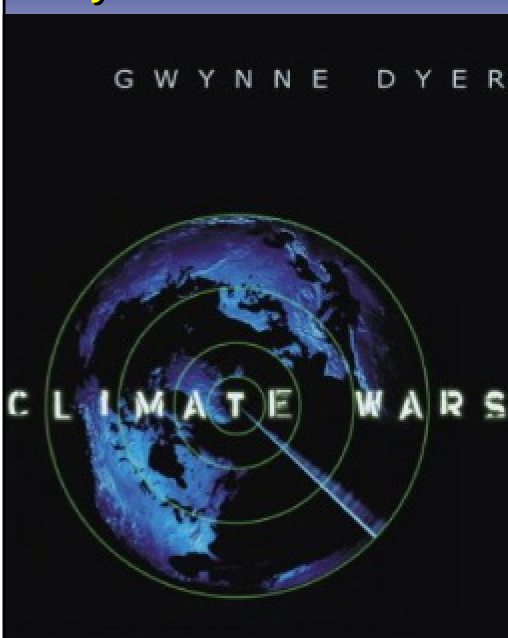
Algae R&D simpler. Why? More tractable organisms (?)

Algae deployment could be much faster if really needed

Algae have multiple benefits. What? wastewater treatment, protein and other co-products

Algae can use water (e.g. seawater) and land unsuitable for crop production.

Why we need all biofuels: Global Warming!



(from the book jacket):

"...the geopolitical conflicts that may unfold over the next few decades [are] almost too fearsome to absorb...

[among] the scientists themselves, there is a palpable sense of panic, something confirmed by Dyer in his interviews conducted around the world."


ANY QUESTIONS?